Midterm results of mitral valve repair with artificial chordae in children

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Objective: We have used artificial chordal replacement with expanded polytetrafluoroethylene sutures for mitral valve repair in children and reported favorable early clinical results. In this article we evaluate the midterm results of mitral valve repair with expanded polytetrafluoroethylene sutures in 39 children.

Methods: From April 1995 through September 2003, mitral valve repair with chordal replacement using expanded polytetrafluoroethylene sutures was performed in 39 patients. In all patients the preoperative grade of mitral regurgitation was moderate or more because of prolapse of the anterior mitral leaflet. The mean age and body weight at the time of the operation were 4.7 ± 5.3 years (range, 1 month to 17.8 years) and 14.4 ± 12.2 kg (range, 3.9-54.4 kg), respectively. The number of expanded polytetrafluoroethylene sutures ranged from 1 to 3 (mean, 1.4). The mean follow-up period and body weight at the latest follow-up were 5.0 ± 2.3 years (range, 1.1-8.5 years) and 25.7 ± 16.4 kg (range, 6.9-73 kg), respectively.

Results: There were no operative or late deaths. Only one patient required mitral valve replacement, which occurred 17 days after repair. Two patients underwent redo mitral valve repair 2 and 5 years after initial repair, respectively. The actuarial freedom from reoperation at 5 and 8 years was 94.8% and 89.5%, respectively. At the latest follow-up, trivial or less mitral regurgitation was observed in 33 (84.6%) patients.

Conclusions: Mitral valve repair with expanded polytetrafluoroethylene sutures in children demonstrated favorable midterm outcome. The procedure is safe and effective, with potential for patients' growth.

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For mitral valve (MV) reconstruction, various techniques have been used to avoid prosthetic valve replacement, especially in children. Recently, MV plasty in children has gained popularity, and its operative results are satisfactory.[1-3] However, mitral regurgitation (MR) caused by anterior leaflet prolapse is sometimes more difficult to repair with a simple method, such as triangular resection, chordal shortening, or chordal transfer.[4,5]

Chordal replacement with expanded polytetrafluoroethylene (ePTFE) sutures was introduced as an alternate technique for MV repair, and favorable early outcomes have been reported, including our previous study.[1,6] Recently, this procedure has become an essential component in the armamentarium for MV plasty in children. However, the long-term durability and biologic adaptation of ePTFE sutures after patient growth has been a great concern. Therefore, in this study we evaluated the midterm effectiveness of chordal replacement with ePTFE sutures for MV repair in 39 children operated on during the past 8 years.

Patients and Methods

Patients

From April 1995 through December 2003, we performed MV repair with chordal replacement using ePTFE in 39 children. The patient group consisted of 9 male and 30 female subjects with a mean age of 4.7 ± 5.3 years (range, 1 month to 17.8 years) and body weight at the time of the operation of 14.4 ± 12.2 kg (range, 3.9-54.4 kg). A total of 11 (28.2%) of 39 patients underwent MV repair before 1 year of age. The grade of MR at the operation was moderate in 34 (89%) patients and severe in 5 (13%) patients. All patients had anterior mitral leaflet prolapse (39/39 [100%]) that was caused by chordal elongation in 20 (51%) patients, torn chordae in 14 (36%) patients, and absent chordae in 5 (13%) patients. Associated cardiac anomalies were present in 23 (59%) patients, as shown in Table 1. Nine patients had a history of previous cardiac operations, including MV plasty in 3 patients, closure of ventricular septal defect in 2 patients, closure of atrial septal defect in 1 patient, bidirectional Glenn procedure in 1 patient, ligation of patent ductus arteriosus in 1 patient, and central shunt in 1 patient. Informed consent was obtained from patients before surgical intervention, and this study was approved by our institutional review board.

TABLE 1. Associated cardiac anomalies

	N	(%)
No cardiac anomalies	16	41
Ventricular septal defect	9	23
Atrial septal defect	4	10
Bland-White-Garland syndrome	2	5
Left coronary artery obstruction	2	5
Pulmonary atresia/intact ventricular septum	1	3
Complete form of atrioventricular septal defect	1	3
Tricuspid atresia	1	3
Double-chambered right ventricle	1	3
Patent ductus arteriosus	1	3
Double aortic arch	1	3

Indications for MV Repair

The indication for surgical intervention was based on the experience of our institution. Medical therapy, including angiotensin-converting enzyme inhibitors and diuretics, were initiated by referring pediatric cardiologists. Before surgical consultation, most of the patients experienced severe MR. Moderate or severe MR, despite optimal medical treatment, with an episode of congestive heart failure and significant morphologic changes of the anterior leaflet prolapse is our indication for surgical intervention. Pulmonary hypertension (mean pulmonary artery pressure > 20 mm Hg by means of a Swan-Ganz catheter) was observed in 25 (64%) patients. Preoperative ventilator support was necessary in 6 (15%) patients.

Surgical Procedures

Our original procedure was described previously, as shown in Figure 1.[1] In brief, during cardiopulmonary bypass the MV was approached through a left atriotomy (34 patients) or atrial septostomy (5 patients). We placed double-armed mattress sutures of 4-0, 5-0, or 6-0 ePTFE reinforced with felt pledgets between the papillary muscle and free margin of the anterior leaflet. The length of the ePTFE sutures was adjusted with the adjacent normal anterior leaflet or facing posterior leaflet. When the prolapsed portion was wide, another ePTFE suture was placed in the same fashion. The number of ePTFE sutures ranged from 1 to 3 (mean, 1.4; 1 suture in 25 [64%] patients, 2 sutures in 12 [31%] patients, and 3 sutures in 2 [5%] patients). In addition, Kay-Reed annuloplasty was performed in all patients to correct annular dilatation. In 18 patients concomitant repair of a congenital cardiac anomaly was performed. After completion of MV repair to examine the competency of the MV, the left ventricle was filled with fluid injected across the MV into the left ventricle. Valvular function and anatomy were further assessed with transesophageal or epicardial echocardiography while the patient was weaned from cardiopulmonary bypass. All patients received warfarin anticoagulation for 3 months postoperatively.

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Follow-up

Follow-up was completed in all patients, with a mean period of 5.0 ± 2.3 years (range, 1.1-8.5 years). The mean body weight at the latest evaluation was 25.7 ± 16.4 kg (range, 6.9-73.0 kg). During the follow-up period, all patients were evaluated annually by transthoracic echocardiography at our hospital. If multiple echocardiographic measurements were obtained, the latest one was taken into the analysis. The normal size of the mitral annular diameter and the left ventricular diastolic dimension were calculated from body surface area, according to the method of Kirklin and Barratt-Boyes.[7]

Functional Assessment of the MV

To assess the adaptability of ePTFE sutures in accordance to the patients' growth, we measured (1) the distance between the plane of the mitral annulus and the top of the papillary muscle (AP distance) and (2) the diameter of the mitral annulus (MV diameter) at the end-systolic phase, as shown in Figure 2. The AP distance reflected the depth of the mitral coaptation zone and the length of the artificial chordae. The ratio of MV diameter to AP distance was calculated and was compared with that of 50 control children with normal hearts (age, 4.2 ± 3.1 years [range, 2 months to 10.8 years]; body weight, 15.7 ± 10.1 kg [range, 1.9-44.3 kg]).

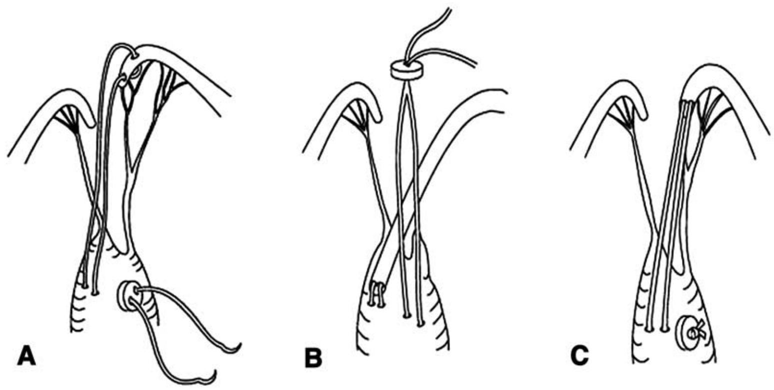

Figure 1. Surgical method of MV repair. A, A double-armed ePTFE suture was passed through the rough zone of the prolapsed leaflet and through the papillary muscle at 3 to 4 mm from its top. The sutures were then passed through a pledget on the side of the muscle, where the sutures emerged from the papillary muscle. B, This suture was drawn until the leaflet was drawn to the papillary muscle. The knot was then tied a little longer than at the level of the opposing normal leaflet. C, The new chordae were then pulled back through the papillary muscle until the pledget came up against the muscle.

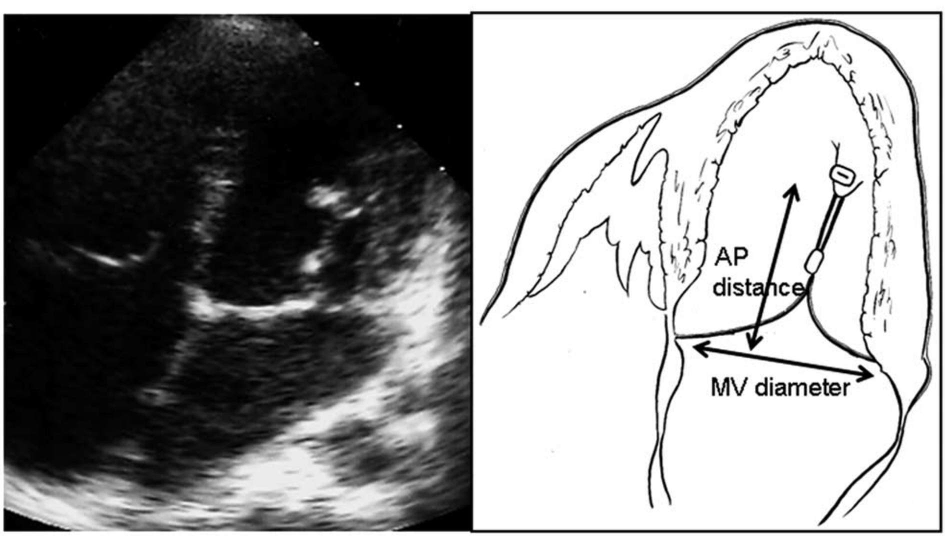

Figure 2. Postoperative echocardiography in 4-chamber view at the end-systolic phase. *MV diameter*, Diameter of the mitral annulus; *AP distance*, distance between the mitral annulus and the top of the papillary muscle.

Data Analysis

The continuous data in this study are expressed as mean values ± SD. Paired *t* tests were performed to analyze the differences between variables. Freedom from reoperation was calculated by the Kaplan-Meier method and expressed as mean values ± SE. Statistical analysis was performed with StatView (SAS Institute, Cary, NC).

Results

Surgical Results

There were no hospital deaths. The preoperative and postoperative grades of MR are shown in Figure 3. A 3-month-old boy had residual MR with symptoms of heart failure during the hospital stay. His MR was trivial immediately after the operation, but it became more significant over 15 days after the operation, requiring endotracheal intubation and inotropic support to control heart failure. The patient was taken back to the operating room for redo MV surgery. Transthoracic echocardiography after achievement of general anesthesia demonstrated moderate MR, and rupture of the chordae was suspected. At the time of the operation, all ePTFE artificial chordae were intact; however, friable leaflets and multiple de novo chordal ruptures were encountered. The MV could not be repaired, and therefore MV

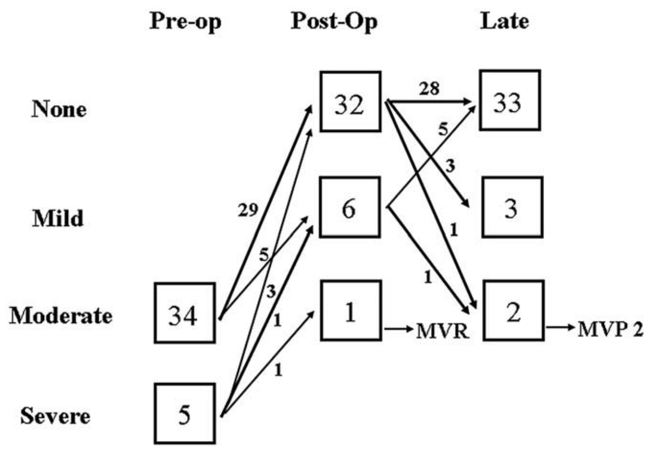

Figure 3. Comparison of preoperative and postoperative MR. One patient underwent MV replacement after the operation, and 2 additional patients underwent redo MV repair in a late follow-up period.

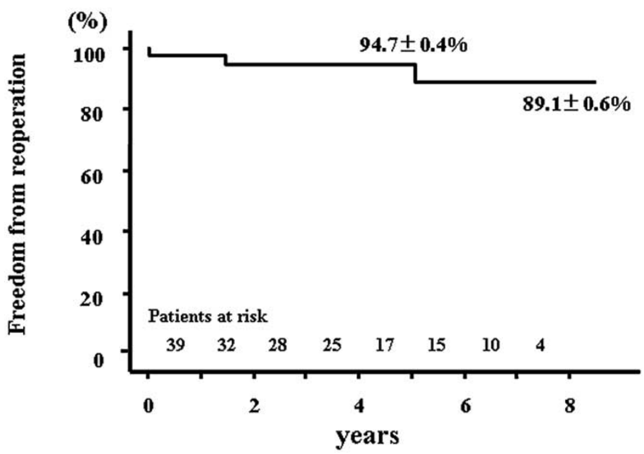

Figure 4. Actuarial freedom from reoperation after MV repair with ePTFE sutures.

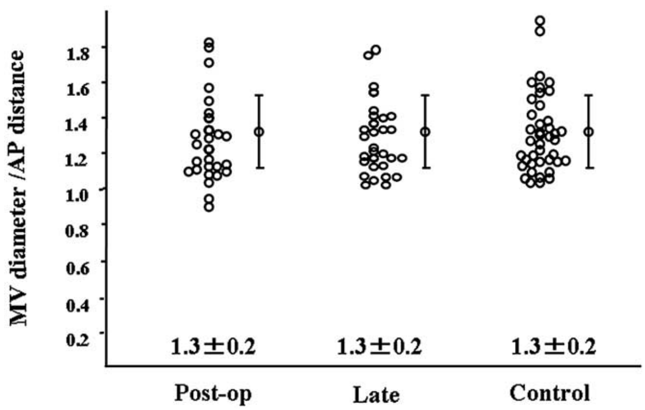

Figure 5. Ratio of the diameter of the mitral annulus to the distance between the plane of the mitral annulus and the top of the papillary muscle, as measured by means of echocardiography *(MV diameter/AP distance)*.

replacement was performed with a 16-mm mechanical prosthesis.

Clinical Follow-up Results

During follow-up, the degree of MR was recorded as shown in Figure 3. A total of 36 patients had mild or less MR at the latest follow-up echocardiography. Two patients with moderate MR underwent repeat MV plasty. A 5-month-old boy who had anterior leaflet prolapse underwent repeat MV plasty with ePTFE sutures 2 years after the initial operation. A 6-year-old girl who had a recurrence of MR related to a partial atrioventricular septal defect underwent closure of the MV cleft 5 years after the initial operation. These 2 patients who required reoperation are currently doing well without significant MR. Among the patients who had preoperatively severe MR (5 patients), 4 patients did not have any MR during follow-up. However, 1 patient (the previously mentioned 5-month-old boy) required redo MV plasty. There have been no late deaths. The actuarial freedom from reoperation was 94.8% ± 0.4% at 5 years and 89.5% ± 0.6% at 8 years, as shown in Figure 4. During the follow-up period, there was no thromboembolism.

Echocardiographic Follow-up Results

Mitral annular diameter, left ventricular diastolic diameter, and mitral flow velocity normalized in all patients on the basis of echocardiography during the follow-up period, as shown in Table 2. Although thickening of ePTFE was observed with time, restrictive movement of the mitral leaflet was not found in any patients.

The ratios of MV diameter to AP distance at early and late follow-up in 39 patients and the control group are shown in Figure 5. These measurements in 16 patients whose body surface area increased more than 1.5 times are shown in Figure 6. The ratio of MV diameter to AP distance at early and late follow-up with a mean interval of 5.0 years was unchanged in 39 patients and similar to that seen in healthy subjects.

Operations for Patients Less Than 1 Year of Age

Eleven patients were younger than 1 year of age. In this younger group the mean age and body weight at the time of the operation were 6.9 months (range, 3.5-11.9 months) and 5.5 kg (range, 3.9-8.3 kg). The mean follow-up period and body weight at the longest follow-up were 3.4 years (range, 1.2-6.2 years) and 12.2 kg (range, 6.9-17.0 kg). The grade of MR at the latest follow-up was less than trivial in 6 (55%) patients and mild in 3 (27%) patients. Moderate or more MR

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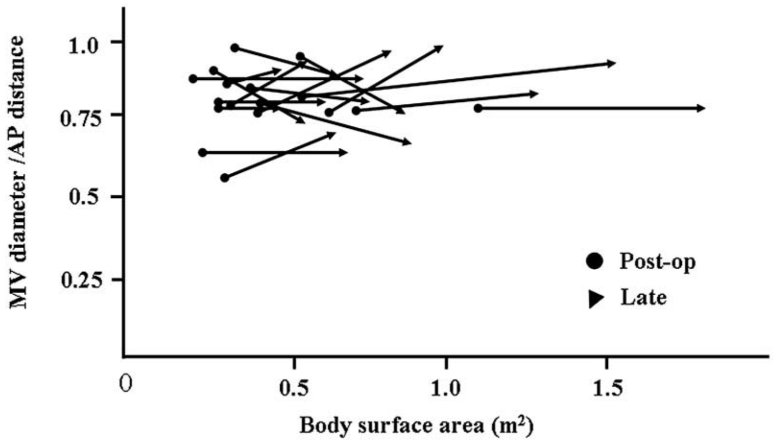

Figure 6. Changes of the ratio of MV diameter to AP distance between postoperative and late follow-up in 16 patients whose body surface areas were increased more than 1.5 times. *AP distance*, The distance between the plane of the mitral annulus and the top of the papillary muscle; *MV diameter*, the diameter of the mitral annulus.

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TABLE 2. Preoperative and postoperative echocardiographic studies of mitral valve

	Before surgical intervention	Before discharge from the hospital	Late follow-up
Annular diameter (mm)	23.6 ± 6.8 (11.0-35.0)	16.0 ± 3.1* (11.3-23.1)	20.1 ± 4.5 (11.8-30.6)
% Normal	150 ± 25	103 ± 27*	105 ± 13
LVDd (mm)	41.9 ± 11.2 (23.0-66.0)	32.4 ± 9.0* (16.0-56.0)	38.0 ± 8.3 (26.0-58.0)
% Normal	146 ± 21	109 ± 14*	108 ± 14
Flow velocity (cm/s)		103 ± 18	115 ± 25

Values are expressed as means ± SD. *LVDd*, Left ventricular diastolic diameter; *BSA*, body surface area.
Predicted normal annular diameter (mm) = 20.1 + 14.5 × *Log(BSA).*
% Normal annular diameter (mm) = [Actuarial measurement of annular diameter]/[Predicted normal annular diameter] × 100
Predicted normal LVDd (mm) = 38 + 32.1 × *Log(BSA).*
*Denotes a statistically significant value when compared with preoperative measurements ($P < .05$).

was found in 2 (18%) patients, and reoperation was performed as described above.

Discussion

Since David and colleagues[8] first described an MV repair method with artificial chordae for the treatment of anterior leaflet prolapse, there have been numerous studies concerning the effectiveness of this procedure. Eishi and colleagues[9] reported actuarial freedom from reoperation for this procedure of 96% at 8 years. However, this technique remained an uncommon procedure in children, probably because of concern for patient growth and a lack of long-term follow-up.

We treated 22 patients with MR caused by anterior leaflet prolapse before the introduction of the chordal replacement technique in our institution. In these 22 patients, 4 mitral valve replacements were performed as a result of failed MV plasty, and the remaining 18 patients underwent MV plasty without chordae repair. One operative death and 2 late deaths occurred. At follow-up, trivial or less MR was observed in 10 (59%) patients, mild MR in 2 (12%) patients, and moderate MR in 5 (29%) patients. Five of these patients with moderate MR underwent reoperations: mitral valve replacement in 4 and MV plasty in 1. The actuarial freedom from reoperation for MV plasty without chordae repair was 85.9% at 5 years and 75.2% at 10 years, with a mean follow-up period of 8.7 ± 6.0 years. These poor results from MV repair without chordae replacement (conventional techniques, such as annuloplasty, leaflet resection, and chordal shortening or translocation) were acceptable. However, management of the anterior leaflet prolapse associated with torn or absent chordae by using conventional techniques alone appeared to be suboptimal. Successful reports of annuloplasty alone in children have been reported previously.[5] However, even in these reports, the late results of MR caused by absent chordae were not always satisfactory, and artificial chordal replacement for those patients was recommended. Chordal replacement is theoretically an ideal indication for patients with torn or absent chordae. In our series there were 19 patients with torn or absent chordae and 20 with elongated chordae, and reoperation was required in 10.5% and

5.0%, respectively. From our limited experience, we believe that chordal replacement can effectively control MR, regardless of the nature of the chordal pathology.

Our follow-up results of artificial chordal placement (reoperation freedom of 94.7% at 5 years and 89.5% at 8 years) appeared to be superior to those of previous studies of MV repair without chordal replacement techniques (eg, 84% freedom at 7 years, as shown by McCarthy and associates[2]), although direct comparison is difficult. Our findings justify the use of ePTFE artificial chordae in children to replace elongated or ruptured chordae tendineae, to reinforce friable chordae, or both, including for patients with severe MR.

These favorable clinical outcomes are supported by echocardiographic follow-up results. Most patients (92%) remained with mild or less MR. Annular distance and left ventricular diastolic diameter were unchanged over the follow-up period. The findings of MV diameter/AP distance ratio were interesting, especially for patients with significant somatic growth (Figure 6). The MV diameter/AP distance ratios became normal heart measurements at the time of the operation and remained unchanged for years after the operation (Figure 5). This suggests that once the relationship of the valve leaflets and subvalvular apparatus is corrected by surgical intervention, it will stay in normal proportions afterward. Because of the nearly normal mitral annular diameter and the unchanged ratio of MV diameter to AP distance in the follow-up period, the AP distance must have increased over the years after surgical intervention as the child grew. These observations might be explained by a compensatory extensive growth of the mitral leaflet and papillary muscle in the patients who underwent chordal replacement with ePTFE, a type of biologic adaptation. Three-dimensional echocardiographic analysis would be helpful to obtain more accurate geometry of the MV to confirm our theory.[10,11]

MV plasty in the patients younger than 12 months can be difficult because of the complex morphology, nature, and friability of mitral leaflets and the small operative field. Congenital MR is often associated with subvalvular anomalies, such as papillary muscle hypoplasia, which makes MV repair more complex. Surgical exposure of the MV for these small children can be accomplished with an extended left atriotomy with transection of the superior or inferior vena cava. We believe our midterm results of MV repair with artificial chordae for these young patients are within the acceptable range: 8-year survival of 100% and reoperation-free rate of 82%. A comparable study of MV repair for patients aged 12 months or younger was reported by Uva and coworkers,[4] with a 7-year survival of 94% and a reoperation-free rate of 58%.

In adults annuloplasty with a prosthetic ring is considered an essential part of the operation to prevent annular dilatation. However, it would not be the procedure of choice for children undergoing rapid somatic growth. The possible problems related to implantation of a prosthetic ring are 3-dimensional annular motion mismatch, posterior leaflet immobilization, and valve distortion.[12] Thus, we applied Kay-Reed annuloplasty as a part of MV leaflet repair.

This study was limited as a retrospective single-center experience. Continued surveillance is necessary to confirm long-term results.

In conclusion, the midterm outcomes for repair of anterior prolapse of the MV with ePTFE chordae in children were favorable. The echocardiographic study of MV apparatus suggests that this procedure has potential benefits for the patient who will undergo somatic growth.

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Discussion

Dr Joseph A. Dearani *(Rochester, Minn)*. I congratulate and commend Dr Minami and colleagues for this important contribution in the use of artificial chordae during MV repair in small children. Your technique of artificial cord placement is elegant, simple, and reproducible, and it adds to the surgeon's armamentarium of repair options when addressing mitral and, occasionally, tricuspid regurgitation.

The major strength of your review and the important message to surgeons is that no apparent negative effect of placing artificial chordae in a growing child was demonstrated in the early-to-midterm follow-up of 5 to 8 years.

Thorough and careful echocardiographic examinations of the MV anatomy were performed. The authors determined that the ratio of MV diameter to the distance between the plane of the mitral annulus and the top of the anterior papillary muscle did not change when compared with that seen in control subjects, despite the presence of considerable somatic growth. Their findings of good valve function, preserved leaflet mobility, and the absence of valve tethering in the vast majority of patients is reassurance to clinicians that the use of artificial chordae does not appear to be detrimental. Longer follow-up with additional somatic growth is required to see whether this finding remains true.

The challenge that the authors have is convincing us whether artificial chordae were, in fact, necessary for successful repair in many of their patients because 100% of patients also had concomitant annuloplasty.

You noted that half of your patients, 51%, had anterior leaflet prolapse with intact chordae, the other half having unsupported segments caused by torn or absent chordae. Given the fact that it has been shown that proper annuloplasty alone can effectively reduce or eliminate MR as a result of isolated leaflet prolapse with intact chordae, it is difficult to know how essential it was to place chordae in the group of patients who had no unsupported segments.

I agree with the authors, and it has been our practice to use artificial chordae to treat an unsupported segment of the anterior leaflet for successful valve repair.

My questions are as follows. First, only 13%, or 5 patients, had severe MR preoperatively. Could you comment on the late results of these particular patients?

Second, what was the outcome of the group of patients with unsupported segments of the anterior leaflet?

Third, do you use leaflet resection or artificial chordae for the management of a flail posterior leaflet?

Dr Minami. To answer the first question, there was no link to MR in 4 patients at the latest follow-up; however, a 5-month-old boy required redo MV plasty 2 years after the initial operation because of new anterior leaflet prolapse. And the second question is about prolapse of anterior mitral leaflets?

Dr Dearani. As to the 50% of patients who had an unsupported segment of the anterior leaflet, the ones who truly needed the artificial chordae, how did they do compared with the patients who had an intact chordae?

The difficulty that I have, when the cords are intact, is that it is hard to know whether it is important to place artificial cords if you do an annuloplasty anyway. The patients who truly need the cords are the ones who have absent chordae or torn chordae. How did those patients do in late follow-up? Because if there is a problem with the artificial cord, then they will be more likely to have recurrent regurgitation. Did those patients do as well as the ones who had cords that were not disrupted? Was there a difference between the 2 groups? Does that make sense?

Dr Minami. In 19 patients with torn or absent chordae, less than trivial MR was observed in 16 (84%) patients, mild MR in 1 patient, and moderate MR in 2 patients at the latest follow-up. Two patients with moderate MR required reoperations 17 days and 2 years after repair. In another group with elongated chordae, less than trivial MR was observed in 17 (85%) patients, mild MR in 2 patients, and moderate MR in 1 patient, who required reoperation 5 years after repair. There was no difference between the 2 groups in late outcome.

Dr Dearani. When you have a ruptured cord to the posterior leaflet, do you put an artificial cord, or do you do a little resection of the leaflet?

Dr Minami. We have never introduced artificial chordae for posterior leaflet prolapse. We could correct them by using leaflet resection and mitral annuloplasty.

Dr Alain Carpentier *(Paris, France)*. I do not want to embarrass you, but I think this is a very important article to be discussed. I congratulate you for demonstrating that contrary to what we could expect, you have not seen any restricted leaflet motion after the use of artificial cords.

It does not mean that this is the ideal solution because the fact that you overnarrow the orifice with a Reed annuloplasty does not provide a normal physiology of the MV, as pointed out by the first discussant.

My only question is as follows: Why do you use artificial cords, which cannot increase their length as the heart grows, rather than native cords? There are always enough native cords that can be transposed from one leaflet to the other or from one location (basal or intermediate chords) to another location (marginal). It is a very reliable technique.

I have operated on several hundred children, including 120 or 130 with congenital malformations, without finding it necessary to use artificial cords. Why do you think it is necessary to follow the current tendency of using artificial rather than natural materials?

Dr Minami. Our ideal operation for MR is perfect repair only with natural material. We used to try chordal transfer and wedge resection, as you have described in the literature, until 1995, and therefore before the first period. But the operative results were not satisfactory, with many reoperations and deaths. We could not anticipate operative outcome after repair, and therefore we changed to use of artificial chordae.

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